

The X-ray off-state of the supersoft source CAL 83 and its interpretation

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Received in original form

ABSTRACT

We consider simultaneous optical data obtained during the recent X-ray turn-off of CAL 83. Combining the optical behaviour with the observed X-ray decay time, we show that a model of cessation of steady nuclear burning is viable if the white dwarf is massive. Our model provides a natural explanation for the subsequent return of the supersoft X-ray emission.

Key words: accretion, accretion discs – binaries: close – binaries: spectroscopic – X-rays: stars – Stars: individual: CAL 83

1 INTRODUCTION

CAL 83 is considered to be a prototypical supersoft X-ray source (SSS; see e. g. Kahabka & Trümper 1996 for a review of these objects). Since its discovery by the *Einstein* X-ray Observatory (Long, Helfand & Grabelsky, 1981), the source appeared to be fairly constant in a number of *ROSAT* observations (e. g. Greiner, Hasinger & Kahabka 1991), but it was found to exhibit variability in some *Einstein* observations (Brown et. al 1994) and in the UV (Crampton et al. 1987; Bianchi & Pakull 1988). Recently, Kahabka (1996) discovered the source to be in an unexpected X-ray off-state, three weeks after it was found to be in a high state. However, a later *ROSAT* pointing, obtained ~ 100 d after the X-ray off-state, revealed the supersoft X-ray emission to have returned to its high state level (Kahabka, Haberl & Parmar 1996). Until now, CAL 83 has been considered to be a persistent SSS. The currently accepted model for the SSS is

that of steady nuclear burning on the surface of an accreting white dwarf (van den Heuvel et al. 1992; Southwell et al. 1996).

In the present letter, we discuss several possible models for the surprising X-ray off-state. We then use new optical observations to distinguish between the models and to determine their viability. Finally, we use what we regard as the most plausible model to place constraints on the parameters of the system.

2 THE X-RAY TURN-OFF AND PROBABLE MODELS

Kahabka (1996) presents three observations with the *ROSAT* HRI. On 1996 March 28, the count rate was 0.206 ± 0.011 s⁻¹, on April 7 it was 0.156 ± 0.012 s⁻¹ and on April 28 it was 0.0047 ± 0.0024 s⁻¹. If it is assumed that the decline

between the first and third observations is exponential, then a decay time of $\lesssim 6$ d is indicated (if the decay was linear, then the characteristic timescale is $\lesssim 20$ d).

If the X-ray turn-off represents an intrinsic change (and is not caused, for example, merely by obscuration of the source; we point out later why this is inconsistent with the observations), then in principle, two models are possible. An X-ray turn-off can be caused either by a drop in the bolometric luminosity, or by a decrease in the effective temperature (or both). In the context of nuclear burning on the surface of a white dwarf, such a change can occur in two different ways (e. g. Prialnik & Kovetz 1995; Krautter et al. 1996). These are: (i) when nuclear burning stops, the white dwarf envelope cools and the luminosity declines back to quiescence, and (ii) if the photosphere of the white dwarf, which is burning nuclear fuel at its surface, expands (as at the onset of a nova outburst), then the effective temperature decreases, thus shifting the emitted power from X-rays to the UV/optical regime. Change (i) above may be expected to occur if the accretion rate decreases, so that it drops below the value corresponding to steady burning. Change (ii) can occur if the accretion rate increases, resulting in the white dwarf expanding to red giant dimensions (e. g. Nomoto 1982).

In order to determine which of these two possibilities might have occurred, we consider optical observations covering the X-ray turn-off period, obtained via the MACHO project (e. g. Alcock et al. 1995). The relevant part of the optical light curve is shown in Fig. 1, where we have marked the dates of the X-ray observations of Kahabka (1996) with vertical dotted lines. Whilst the optical coverage is rather sparse, the following points can be noted. The first X-ray observation (on March 28, at which time the X-rays were on), is about ten days after a time when the optical was high. The second X-ray observation, in which the X-ray count rate was only slightly reduced, is only a few days before what is a clear optical low state. The third X-ray observation, in which the X-rays were off, occurs when the optical has risen from a minimum, almost to its normal level. The general impression is therefore that of an optical minimum, which precedes by $\sim 10 - 15$ d an X-ray minimum. Such a behaviour is consistent with model (i) above, namely the following sequence of events: (a) the mass transfer rate (and therefore the accretion rate) decreases, (b) the optical luminosity (which is generated mainly in the accretion disc; e.g. Crampton et al. 1996) decreases, and (c) the steady nuclear burning ceases, causing a cooling and contraction of the hot surface layers, and a concomitant turn-off in the X-rays. This behaviour is then similar to that observed in the decline phases of classical novae (e. g. Krautter et al. 1996). Furthermore, we expect that the X-rays should turn back on, shortly after the optical returns to its pre-minimum level and the steady nuclear burning resumes. This is consistent with the most recent *ROSAT* pointing taken ~ 100 d after the X-ray off state, when a count rate of $0.21 \pm 0.04 \text{ s}^{-1}$ was detected (Kahabka, Haberl & Parmar 1996).

It should be noted that in model (ii) above, an entirely different behaviour would have been expected, namely a decline in the X-rays which accompanies *an increase in the optical*; this is inconsistent with the observations. Furthermore, a scenario in which the decline in X-rays and optical light is caused simply by obscuration of the source is also

probably inconsistent with the available data. This is because the supersoft X-rays would certainly be extinguished before any optical decline (e.g. SSS are undetectable as soft X-ray sources in the Galactic plane due to the high column density; van den Heuvel et al. 1992).

3 THE IMPLICATIONS OF THE PROPOSED MODEL ON THE SYSTEM PARAMETERS

We can attempt to use the optical and X-ray data to place some constraints on the system parameters. The decrease in the optical is by at least 0.65 mag. Assuming that the luminosity is generated in the accretion disc, this represents a decrease in the mass transfer rate by a factor $\gtrsim 2.5$ (e. g. Webbink et al. 1987). Given the narrowness of the steady nuclear burning strip in the $\dot{M} - M_{\text{WD}}$ plane (Nomoto 1982), such a reduction can definitely result in a cessation of steady burning. Occasional drops in the mass transfer rate are often observed in nova-like variables and, in particular, in the group of cataclysmic variables known as VY Scl stars (e. g. Honeycutt, Robertson & Turner 1995), and in the binary SSS RX J0513.9-6951 (Reinsch et al. 1996; Southwell et al. 1996). The VY Scl stars are normally found in the orbital period range 3 – 4 hrs, whereas CAL 83 has $P_{\text{orb}} = 1.04$ d. Livio & Pringle (1994) have suggested that the low states in the former systems may be caused by star spots on the surface of the secondary which cover the L_1 point; the short orbital periods are then expected because as the rotation rate of the star (which is coupled to the orbit) increases, so does the level of magnetic activity. However, this model is expected also to work for the SSS, which have longer periods, since the physical quantity which actually characterises the magnetic activity is the Rossby number, P_{rot}/τ_C , where τ_C is the convective overturn time in the envelope (e.g. Schrijver 1994). The secondary in CAL 83 is probably evolved (see van den Heuvel et al. 1992 for a discussion), and thus has a deeper convective envelope (longer τ_C) than a main sequence star. Hence, a level of magnetic activity comparable to the VY Scl stars is definitely possible, despite the longer periods of the SSS. In fact, the orbital period of CAL 83 puts it in the range spanned by the magnetically active RSCVn stars.

Once steady burning stops, the somewhat extended white dwarf envelope cools and contracts. We can use the limits on the decline time for the X-rays ($\sim 6 - 20$ d) to place constraints on the white dwarf mass in the system. A reasonable estimate of the decline time is given by $t_{3\text{bol}}$, the time it takes a white dwarf with nuclear burning at its surface to decline by three magnitudes in its bolometric luminosity. An examination of the results of Prialnik & Kovetz (1995), who calculated $t_{3\text{bol}}$ for an extended grid, reveals that in order to obtain $t_{3\text{bol}} \lesssim 20$ d, the white dwarf mass must satisfy $M_{\text{WD}} \gtrsim 1.3M_{\odot}$. In fact, a decline time as short as $t_{3\text{bol}} = 4.3$ d was obtained for $M_{\text{WD}} = 1.4M_{\odot}$.

Further confirmation of the fact that the white dwarf in the system has to be massive can be obtained by estimating an upper limit to the decline time, using the Kelvin-Helmholtz timescale of the envelope:

$$\tau_{\text{KH}} \approx \frac{GM_{\text{WD}}\Delta m_{\text{env}}}{R_{\text{WD}}L_{\text{WD}}}, \quad (1)$$

where L_{WD} is the luminosity and Δm_{env} is the mass of the envelope. The latter quantity is not known, but we can obtain an upper limit to τ_{KH} by using the envelope mass required to obtain a thermonuclear runaway on the surface of a *cold* white dwarf. The envelope in place during steady burning (on a hot white dwarf) can be significantly smaller than this (e.g. Prialnik & Kovetz 1995). The envelope mass is given approximately (e. g. Yungelson et al. 1995) by:

$$\frac{\Delta m_{\text{env}}}{M_{\odot}} \approx 2 \times 10^{-6} \left(\frac{M_{\text{WD}}}{R_{\text{WD}}^4} \right)^{-0.8}. \quad (2)$$

Substituting Eqn. 2 into Eqn. 1 gives for the upper limit on the decay timescale (scaled with the parameter values of a $1.4M_{\odot}$ white dwarf),

$$\tau_{\text{decay}} \lesssim \tau_{\text{KH}} \approx 116 \text{ days} \left(\frac{M_{\text{WD}}}{1.4M_{\odot}} \right)^{0.2} \left(\frac{R_{\text{WD}}}{2 \times 10^{-3} R_{\odot}} \right)^{2.2} \left(\frac{L_{\text{WD}}}{10^{38} \text{ erg s}^{-1}} \right)^{-1}. \quad (3)$$

An examination of Eqn. 3 confirms the fact that in order to obtain the short observed decay time, the white dwarf needs to be very massive. We should note that the secondary star in CAL 83 is believed to have a mass of $1.5 - 2.0M_{\odot}$ (e.g. van den Heuvel et al. 1992) and therefore that it is unstable to thermal timescale mass transfer even for a massive white dwarf.

The fact that we find the white dwarf to be massive raises the question of selection effects. An examination of the evolution of white dwarfs in the $L - T_{\text{eff}}$ plane, when undergoing nuclear burning, reveals that white dwarfs less massive than $\sim 0.8M_{\odot}$ would not have been detected at all as SSS since they never reach high enough effective temperatures (e.g. Iben 1982). Similarly, the luminosity of the system is also higher the more massive the white dwarf. However, with one system, these selection effects should not be over-emphasised.

4 SUMMARY AND CONCLUSIONS

We have considered optical observations which were taken simultaneously with the recently discovered X-ray off-state of the supersoft X-ray source CAL 83. The simultaneous observations allowed us to present a model, in which a drop in the mass transfer rate causes the cessation of steady nuclear burning, resulting in the X-ray turn-off. The steady burning resumes shortly after the optical returns to its pre-minimum level, causing the soft X-rays to turn back on. On the basis of this model, we predict that the white dwarf in CAL 83 has to be very massive.

Acknowledgments

ML acknowledges support from NASA Grants NAGW 2678 and GO-05499 at the Space Telescope Science Institute. KAS is supported by a PPARC studentship. We are grateful for the support given our project by the technical staff at the Mt. Stromlo Observatory. Work performed at LLNL is supported by the DOE under contract W-7405-ENG. Work performed by the Center for Particle Astrophysics personnel is supported by the NSF through grant AST 9120005. The work at MSSSO is supported by the Australian Department of Industry, Science and Technology. KG acknowledges support from DoE OJI, Alfred P. Sloan, and Cotrell

Scholar awards. CWS acknowledges the generous support of the Packard and Sloan Foundations. WS is supported by a PPARC Advanced Fellowship.

Figure 1. Optical photometry of CAL 83 acquired from the MA-CHO Project (e. g. Alcock et al. 1995). The relative magnitude is plotted for the ‘B’ filter, which is approximately equivalent to the Johnson *V* passband. One sigma error bars are shown. The dotted vertical lines indicate the times of the 3 *ROSAT* X-ray observations of Kahabka (1996). The X-rays were on for the first 2 observations, but had switched off by the time of the third (see Sec. 2).

REFERENCES

- Alcock, C. et al., 1995, *Phys. Rev. Lett.*, 74, 2867
 Bianchi, L., Pakull, M.W., 1988, in *A Decade of UV Astronomy with IUE*, ESA SP-281, p. 145
 Brown, T., Córdova, F.A., Ciardullo, R., Thompson, R., 1994, *ApJ*, 422, 118
 Crampton, D., Cowley, A.P., Hutchings, J.B., Schmidtke, P.C., Thompson, I.B., Liebert, J., 1987, *ApJ*, 321, 745
 Crampton, D., Hutchings, J.B., Cowley, A.P., Schmidtke, P.C., McGrath, T. K., O’Donoghue, D., Harrop-Allin, M. K., 1996, *ApJ*, 456, 320
 Greiner, J., Hasinger, G., Kahabka, P., 1991, *A&A*, 246, L17
 Honeycutt, R. K., Robertson, J. W., Turner, G. W., 1995, in Bianchini, A. et al., eds, *Cataclysmic Variables*. Kluwer, Dordrecht, p. 75
 Iben, I. Jr., 1982, *ApJ*, 259, 244
 Kahabka, P., 1996, *A&A*, in press
 Kahabka, P., Trümper, J.E., 1996 in van den Heuvel, E.P.J., van Paradijs, J., eds, *Proc. IAU Symp. 165, Compact Stars in Binaries*. Kluwer, Dordrecht, p. 425
 Kahabka, P., Haberl, F., Parmar, A. N., 1996, *IAUC* 6467
 Krautter, J., Ögelman, H., Starrfield, S., Wichmann, R., Pfeffermann, E., 1996, *ApJ*, 456, 788
 Long, K.S., Helfand, D.J., Grabelsky, D.A., 1981, *ApJ*, 248, 925
 Livio, M., Pringle, J. E., 1994, *ApJ*, 427, 956
 Nomoto, K., 1982, *ApJ*, 253, 798
 Prialnik, D., Kovetz, A., 1995, *ApJ*, 445, 789
 Reinsch, K., van Teeseling, A., Beuermann, K., Abbott, T.M.C., 1996, *A&A*, 309, L11
 Schrijver, C. J., 1994, in Caillault, J.-P., ed, *ASP Conf. Ser.*, 64, *Cool Stars, Stellar Systems and the Sun*. ASP, San Francisco, p. 328
 Southwell, K. A., Livio, M., Charles, P. A., O’Donoghue, D., Sutherland, W., 1996, *ApJ*, in press
 van den Heuvel, E.P.J., Bhattacharya, D., Nomoto, K., Rappaport, S.A., 1992, *A&A*, 262, 97
 Webbink, R.F., Livio, M., Truran, J.W., Orio, M., 1987, *ApJ*, 314, 653
 Yungelson, L., Livio, M., Tutukov, A., Kenyon, S.J., 1995, *ApJ*, 447, 656

